ANNIE:
The Accelerator Neutrino-Neutron Interaction Experiment

Status and Perspectives

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University of California, Davis

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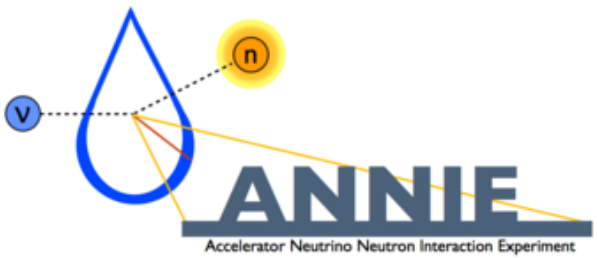
Weak Interactions and Neutrinos 2017 - UC Irvine



UCDAVIS
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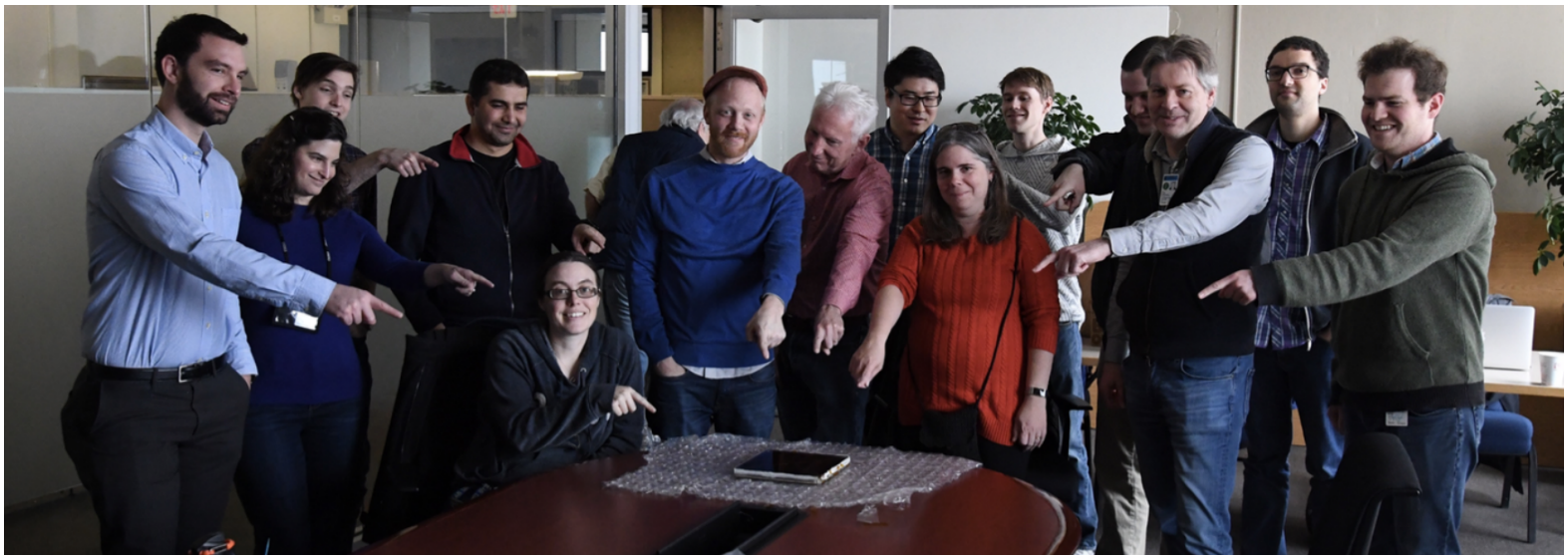
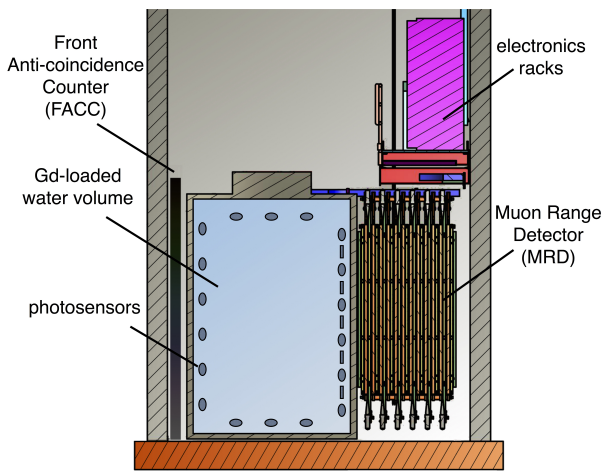
Overview of ANNIE



- **ANNIE** is the Accelerator Neutrino-Neutron Interaction Experiment
- Gd-loaded water Cherenkov detector placed downstream of the Booster Neutrino Beam at Fermilab
- Aims at measuring the production rate of neutrons from neutrino interactions in water
- Proof of concept of a novel kind of photosensors in an HEP experiment
- Currently taking background data (Phase I), soon to be taking physics data (Phase II)

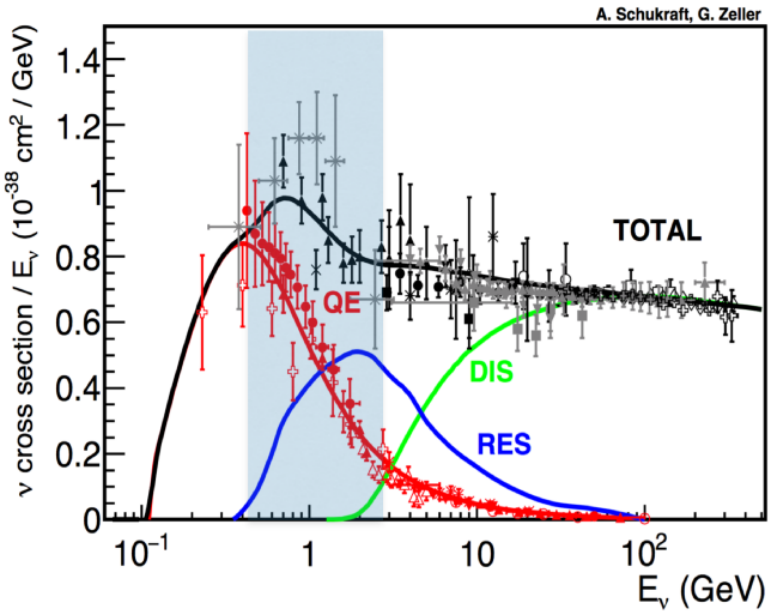


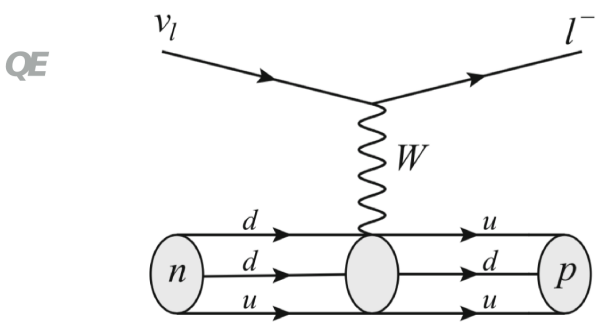
Physics motivation - Energy-dependent neutron yield

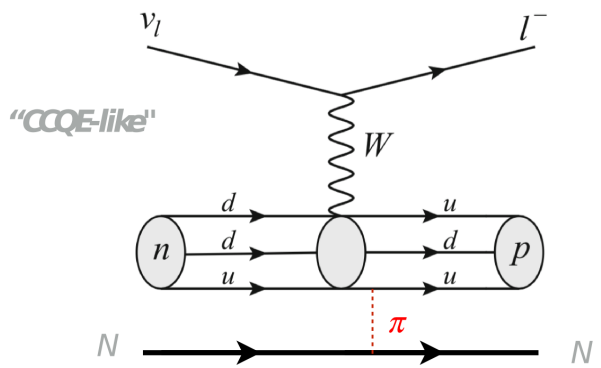
Study the multiplicity of final state neutrons from neutrino-nucleus interactions in water

Long baseline oscillation physics

- Detailed study of "CCQE-like" interactions
- Better identification of pure CCQE interactions and improvement of energy resolution
- Separation of neutrino/antineutrino in a beam
- Complementarity with proton multiplicity measurements in liquid argon







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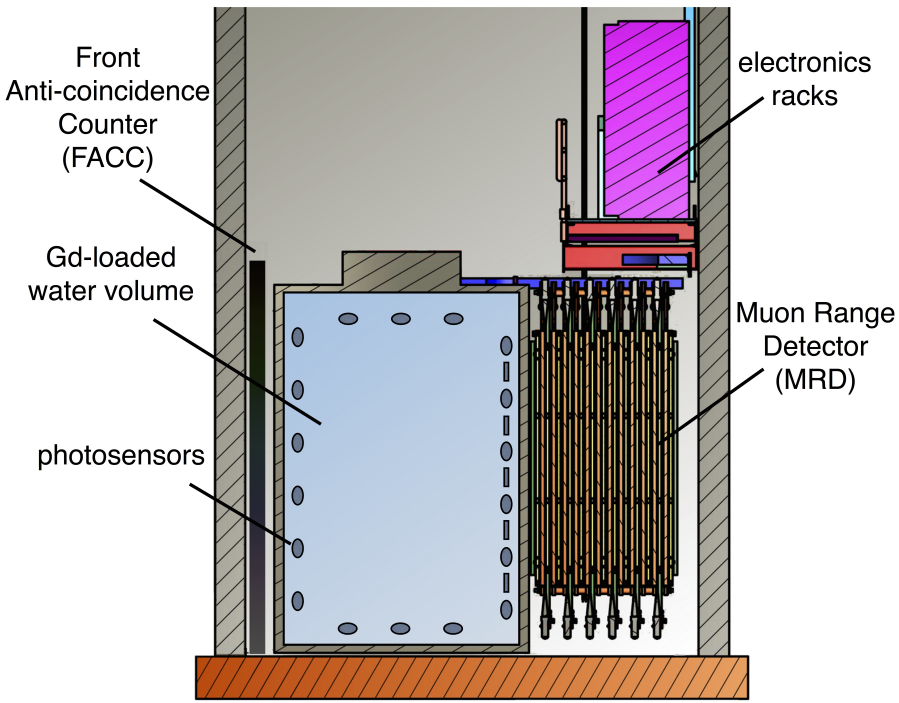
Proton decay and supernova physics

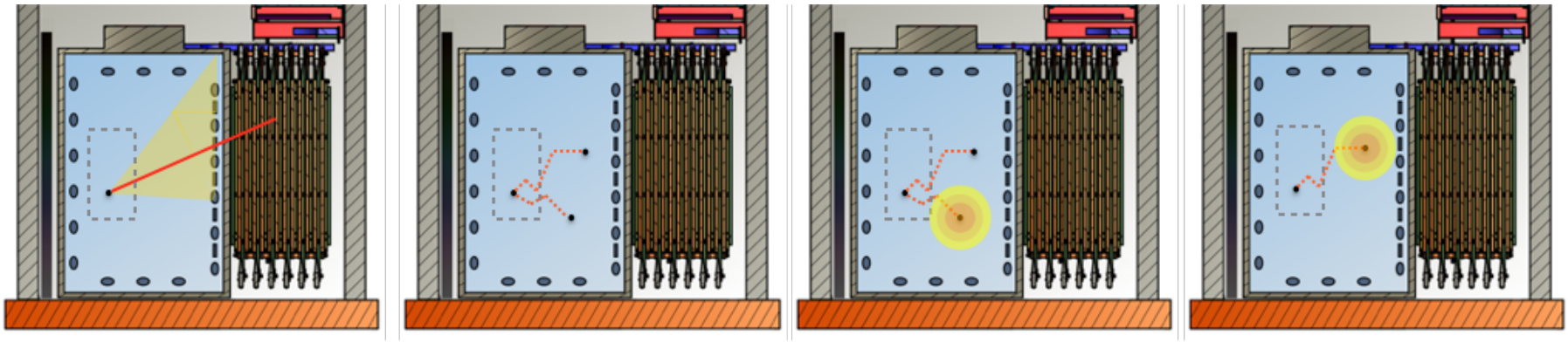
- No neutrons produced in $> 90\%$ of proton decays ($p \rightarrow e^+ + \pi^0$)
- Main background: Atmospheric neutrinos $\rightarrow$ Likely to produce secondary neutrons
- See Prof. Miura's talk on Wednesday
- This can also be applied to help reducing backgrounds for the detection of DSNB (Diffuse SuperNova Background) neutrinos

The ANNIE detector

- Installed in the SciBooNE hall on the BNB line (flux peaked at ∼700 MeV, ROI for atmospheric neutrinos)
- Gadolinium-loaded water volume of 26 tons
- Photosensors: 120 PMTs (8, 10 and 11-inch) and 5 LAPPDs distributed in the tank
- Front veto: Scintillator paddles tagging charged particles originating from the rock upstream
- Muon Range Detector (MRD): Legacy from SciBooNE, steel-scintillator sandwich detector capable of muon direction and energy reconstruction
- ∼14,000 CC interactions per ton per year (2×10^{20} POT) expected



How will ANNIE work?



1 **2** **3** **4**

1 - CC interaction in the fiducial volume

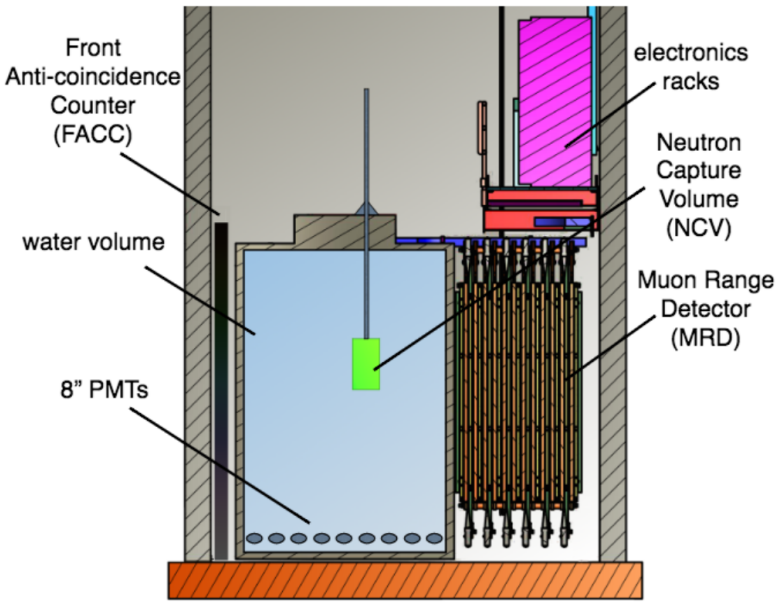
1 - Muon direction reconstructed using LAPPDs

1 - Muon momentum reconstructed with the MRD

2 - Neutrons are getting thermalized in the water volume

3-4 - Neutron capture on Gd detected by the PMTs

ANNIE Phase I - Beam-induced neutron background measurement



- "Proof of concept" → Measurement of the neutron background rate
- Source of neutron background:
  - **Skyshine neutrons** → Neutrons from the beam dump entering the detector
  - **Dirt neutrons** → Neutrons originating from neutrino interactions downstream of the dump
- March-May 2016: Installation in the SciBooNE hall
- Taking data since June 2016 until the 2017 Summer shutdown in July
- Different detector configuration than for the Physics run

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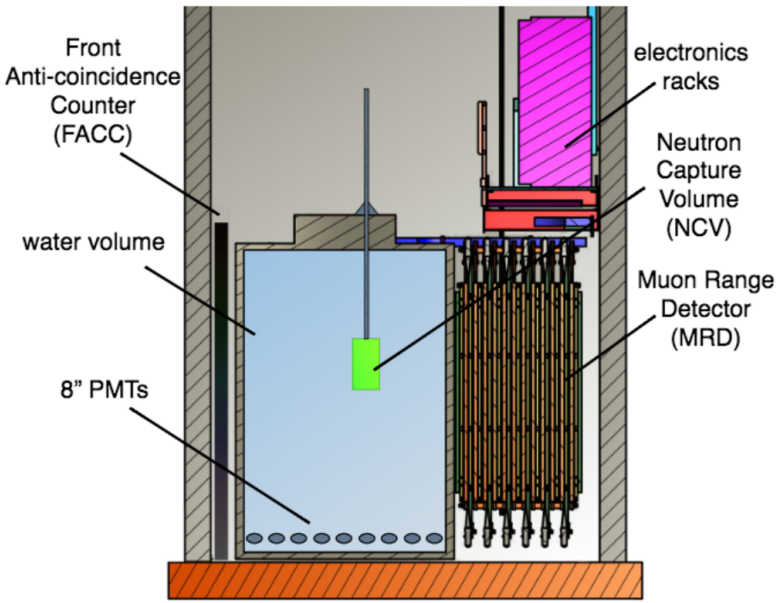

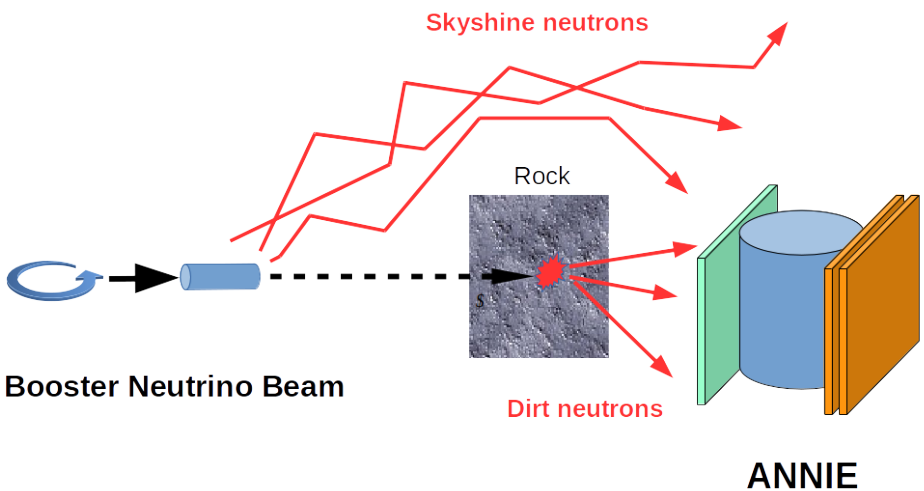

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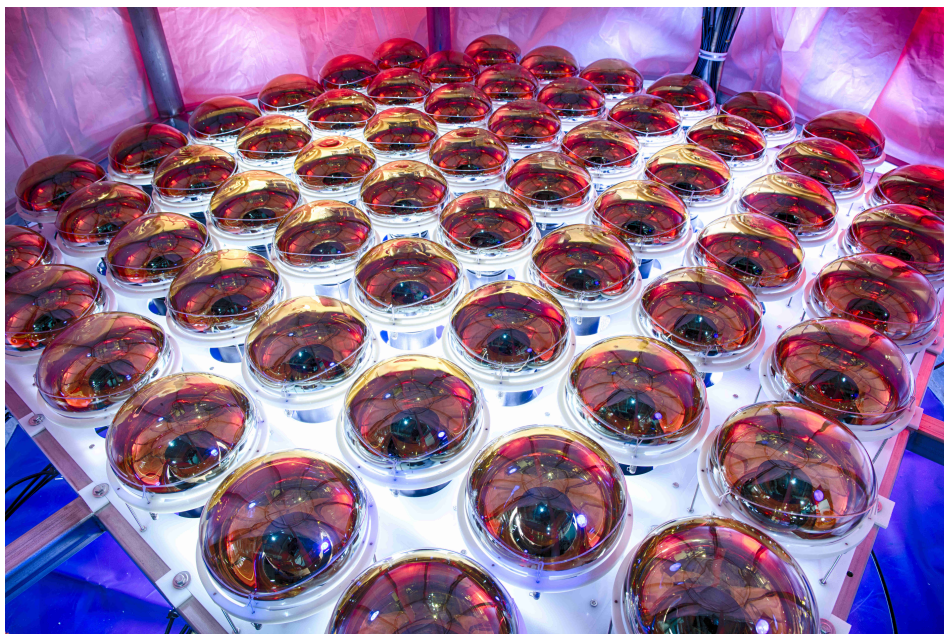
ANNIE Phase 1 - The detector

The tank

- 10'x13' tank filled with 26-ton of unloaded ultrapure water
- Equipped with 60 8-inch r5912 photomultipliers at the bottom



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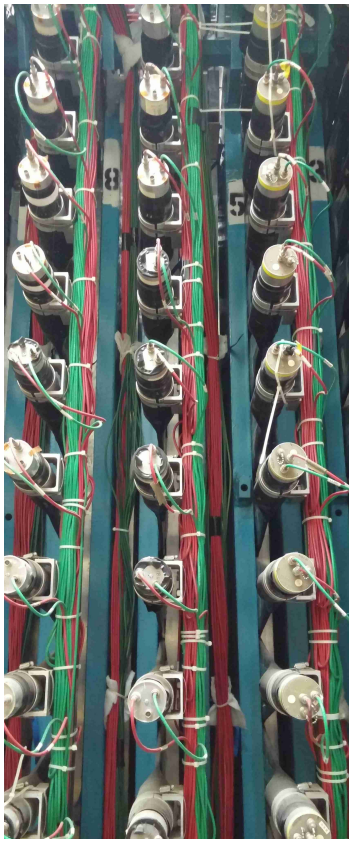

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- First 2 layers in use (55 channels) instead of the 13 layers (362 channels) used in SciBooNE

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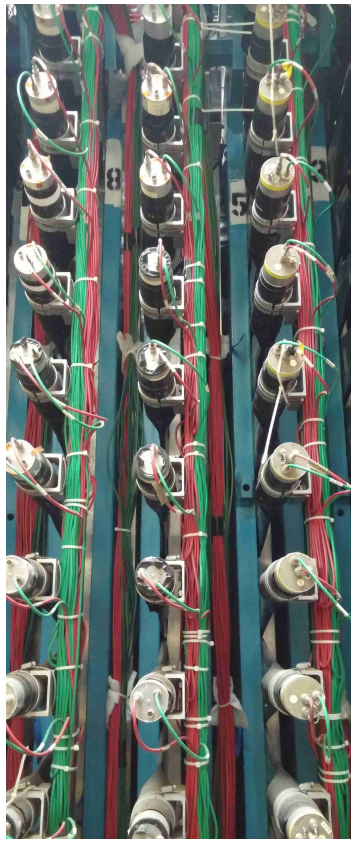

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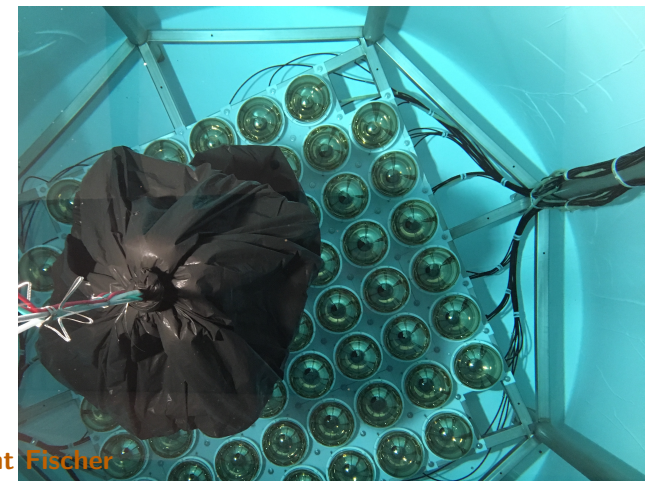

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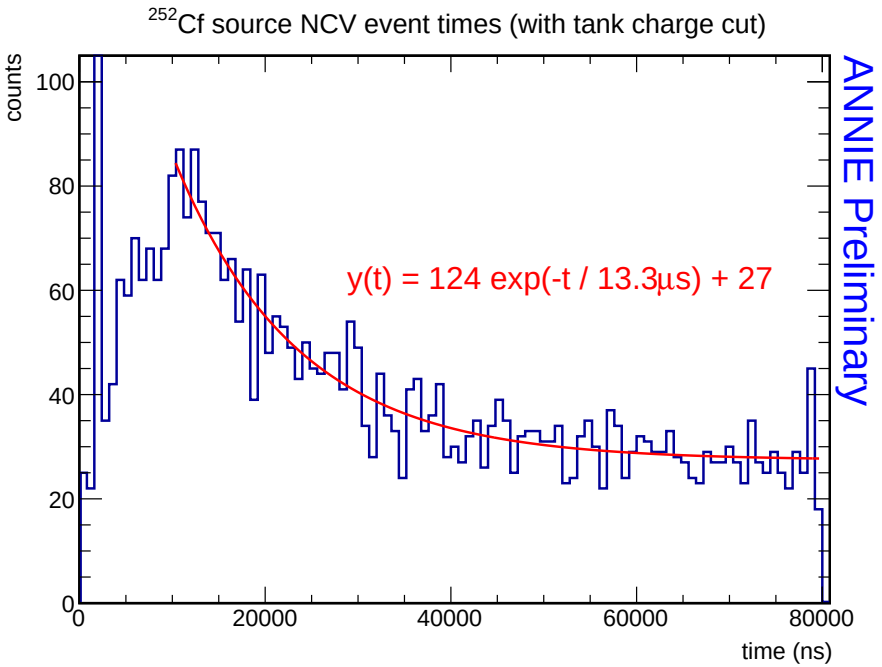
The Neutron Capture Volume (NCV)

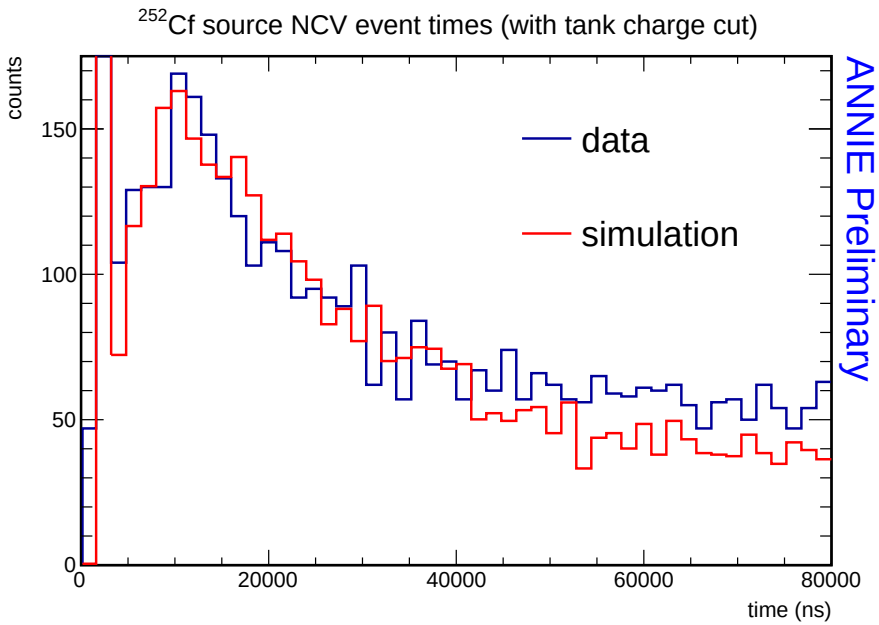
- Neutron-sensitive subvolume within the tank
- 50x50 cm acrylic vessel filled with 100 liters of Gd-doped liquid scintillator (EJ-335, 0.25% Gd)
- Can be moved in the tank using a winch system, optically isolated, instrumented with 2 PMTs

Phase I results - Calibration

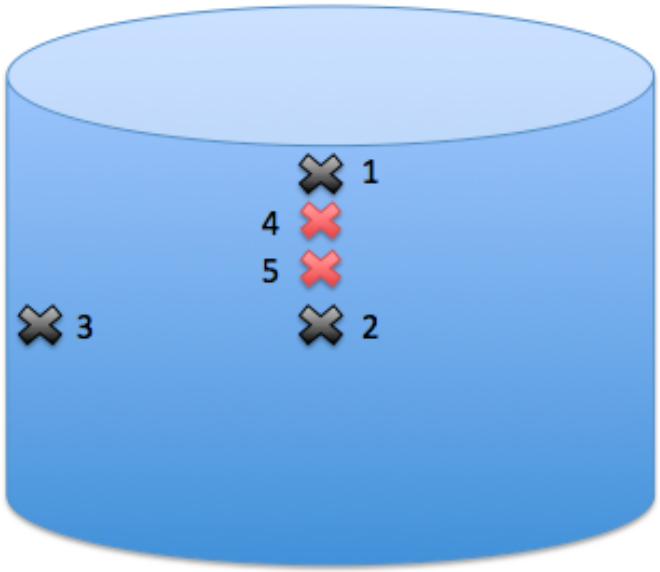
NCV calibration

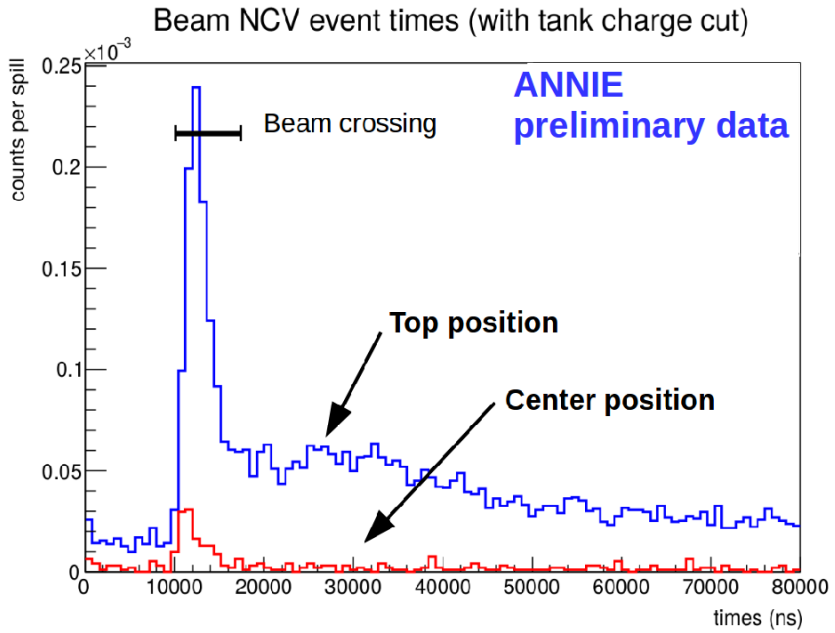
- Understanding the NCV response to neutron captures is crucial
- Use of a self-triggered ^{252}Cf source (n,γ though spontaneous fission)
- Trigger signal sent to the acquisition system, opens a 80 μs acquisition window
- **Results in agreement with simulations**





Phase I results - Neutron background low enough for Phase II

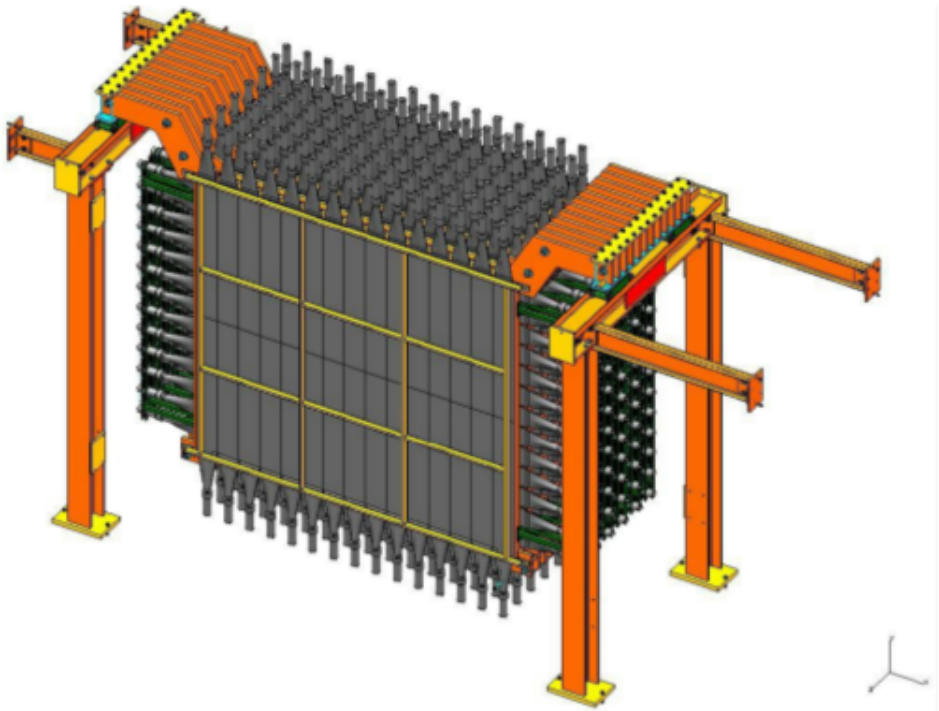




- NCV has been moved to several locations in the tank and data was taken over the last year
- Background neutron flux is different at each position, especially the skyshine component
- Bottom PMTs used as a muon veto (beam and cosmic) along with veto/MRD
- Neutron rate per spill is $< \mathbf{6}\times\mathbf{10}^{-3}$ at the top and $< \mathbf{7.7}\times\mathbf{10}^{-5}$ at the center
- **This neutron background is not an issue for physics**

Towards phase II - Both tank and MRD fully instrumented

- MRD upgrade: 2 layers $\rightarrow$ 11 layers
- Inner structure upgrade to hold more PMTs on all sides
- More conventional PMTs required for Gd captures detection $\rightarrow$ We now have them in hand (LUX, Watchboy, LBNE R&D)
- Gadolinium sulfate ($Gd_2O_{12}S_3$) will be diluted in the water (0.2% w/w)



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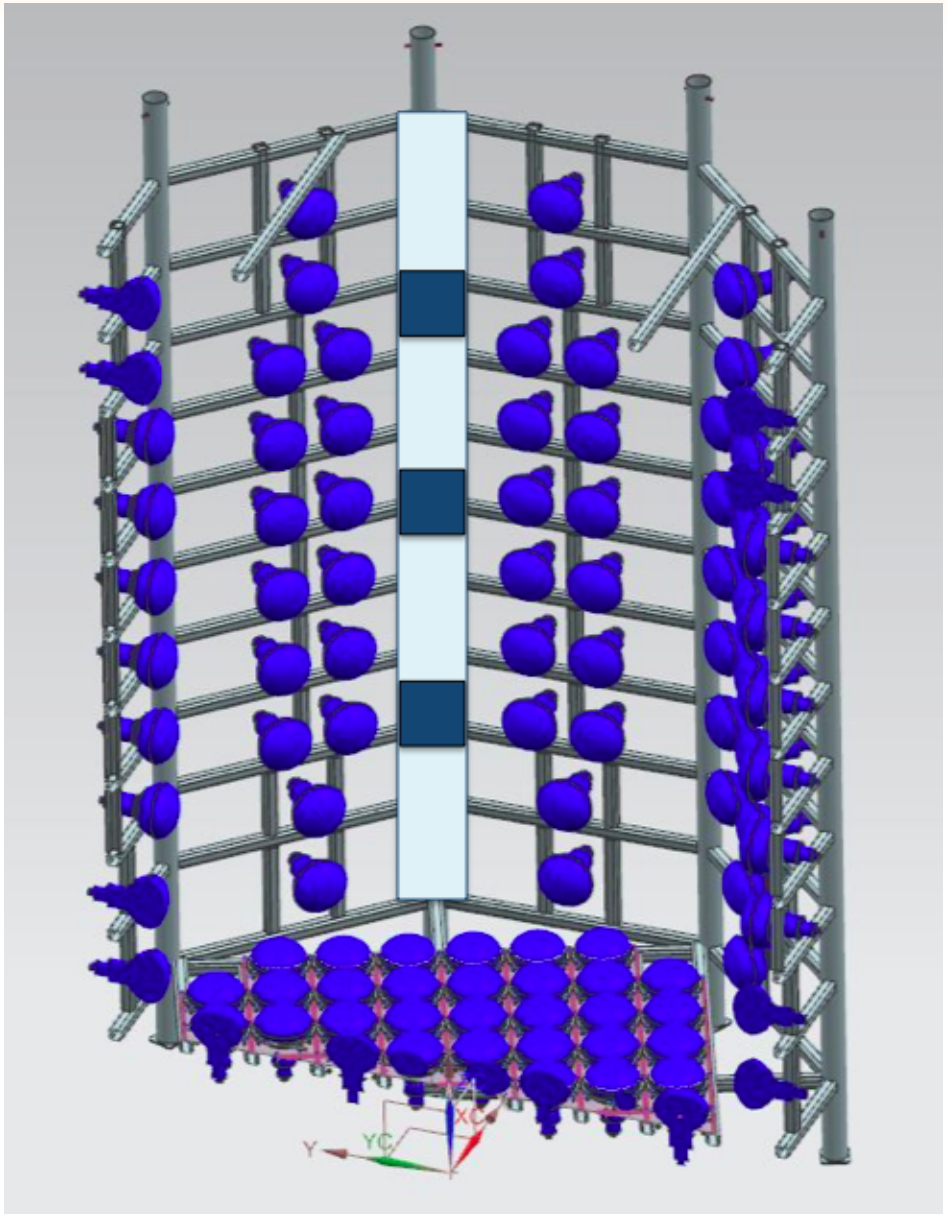

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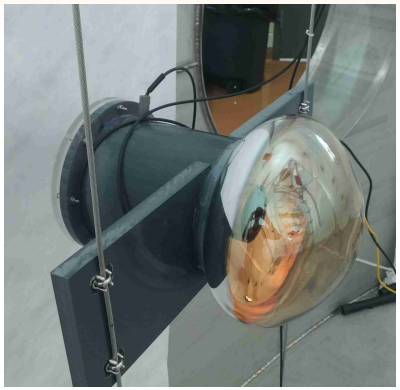

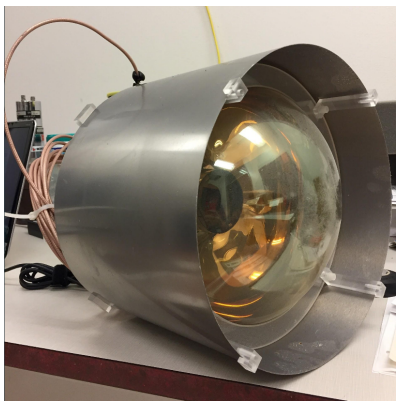

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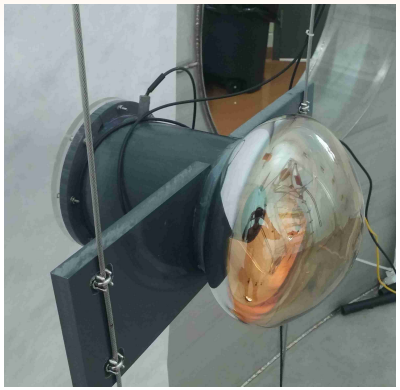
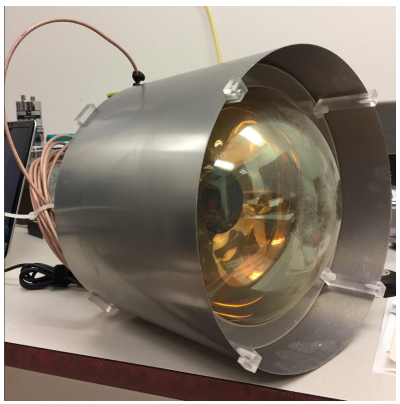
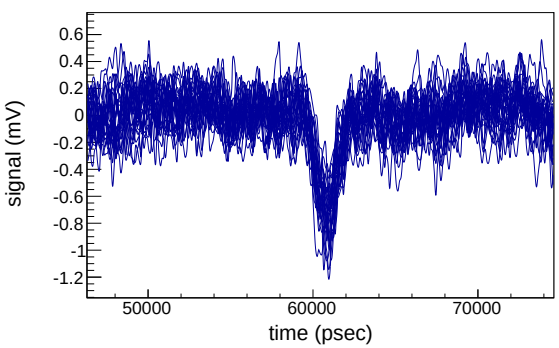


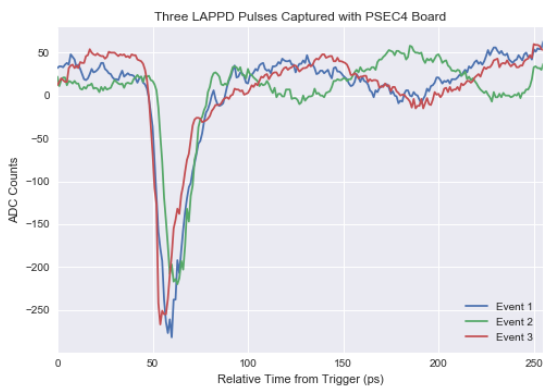


LAPPDs are now available for Phase II

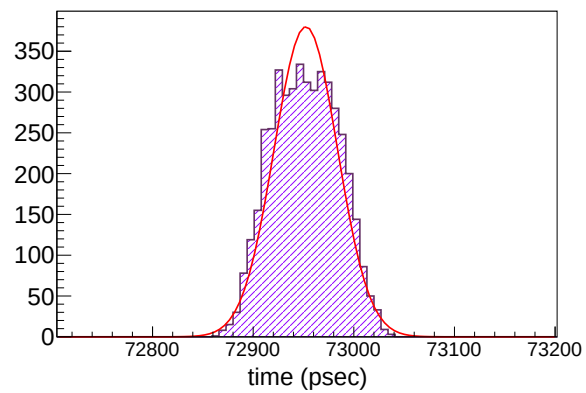
- Operation of LAPPDs in a working neutrino detector → Technological goal of ANNIE
- Incom has now produced several LAPPD prototypes, the most recent almost reaching the specifications set by the ANNIE collaboration (gain, QE, uniformity)
  - Tile #9: sealed with an Al photocathode
  - Tile #10: sealed with multi-alkali photocathode (∼5% QE)
  - Tile #12: ∼5% QE
  - Tile #15: Uniform photocathode with $>$ 25% QE
- Tile #12 is being thoroughly tested at Iowa State University



SPE waveform



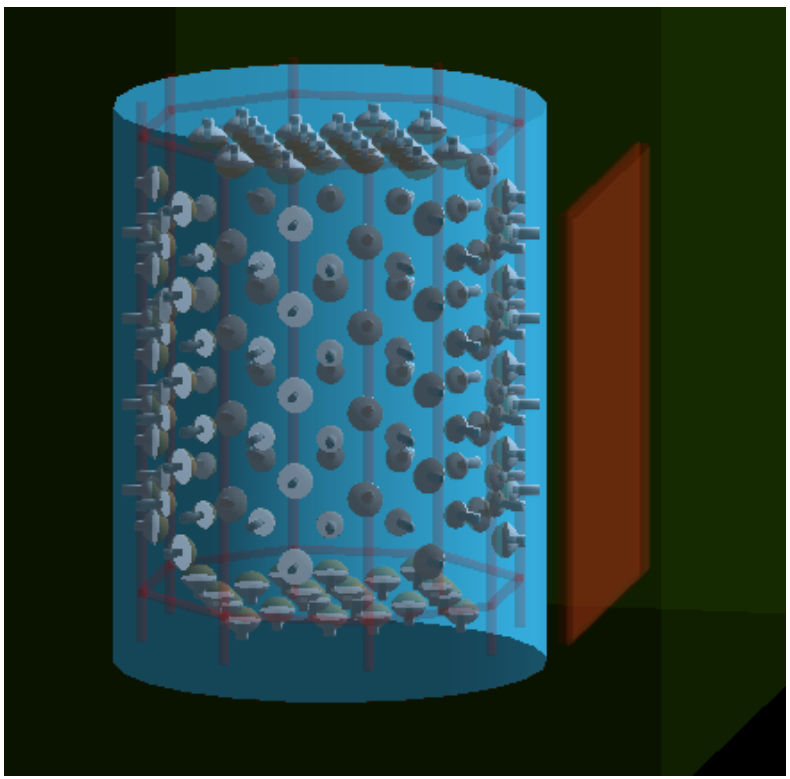
Multi PE waveform

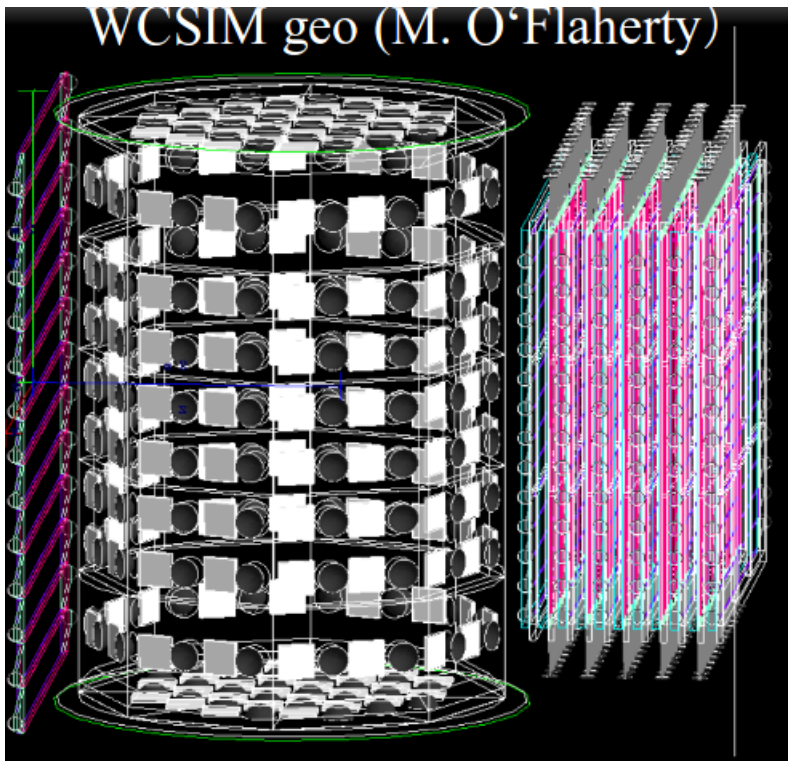


Multi PE TTS

Phase II simulations - Understanding the detector capabilities

- Several simulations packages are used to simulate ANNIE Phase I and II → RAT-PAC (Watchman, SNO+, Theia) and WCSim (Hyper-K)
- Both packages are complementary
- Dataset of ν_μ interactions provided by the GENIE generator
- Neutron detection efficiency studies: 5 p.e. threshold after a neutron capture
- CCQE interaction acceptance studies with MRD penetration
- Vertex reconstruction studies with several LAPPDs and PMTs coverages





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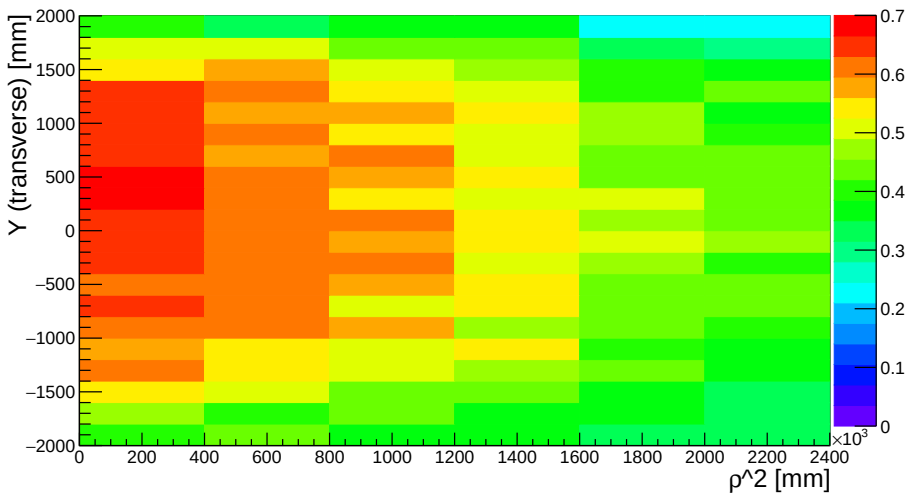

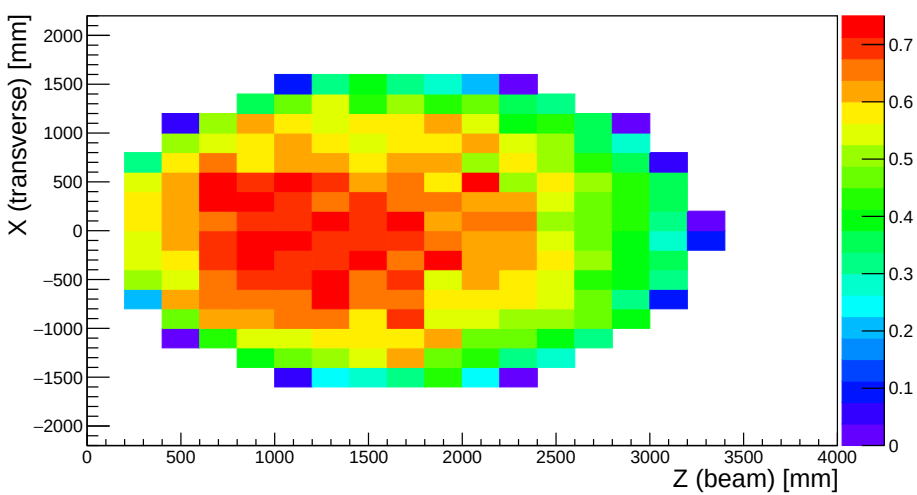

Good neutron detection efficiency in a large fiducial volume

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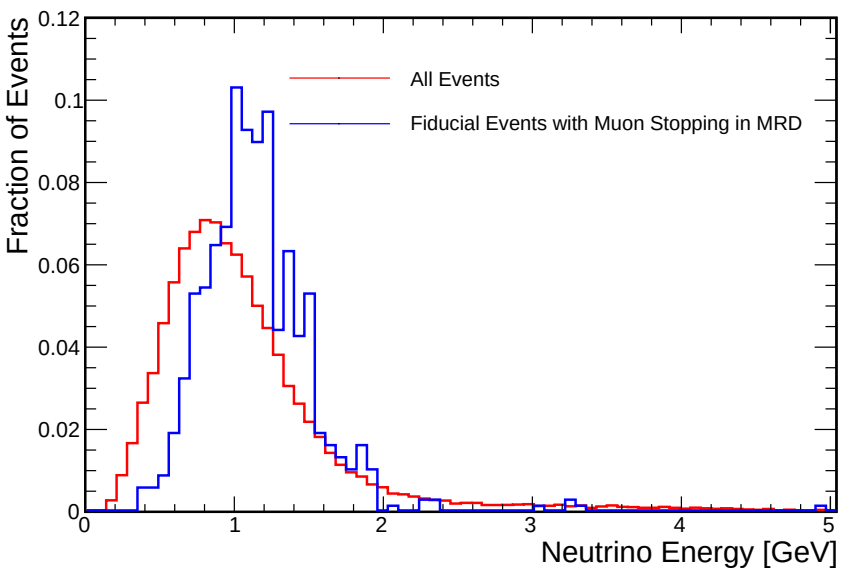

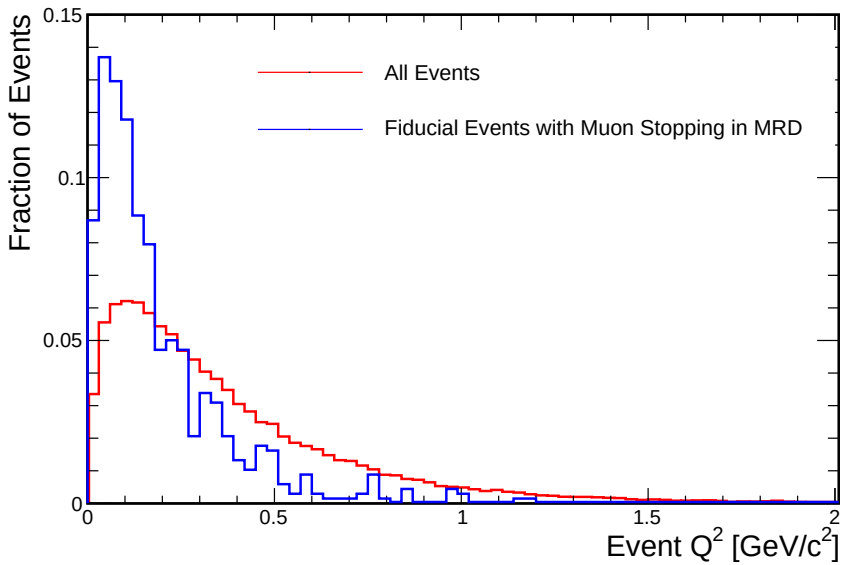

Large CCQE dataset with good track reconstruction and energy estimation

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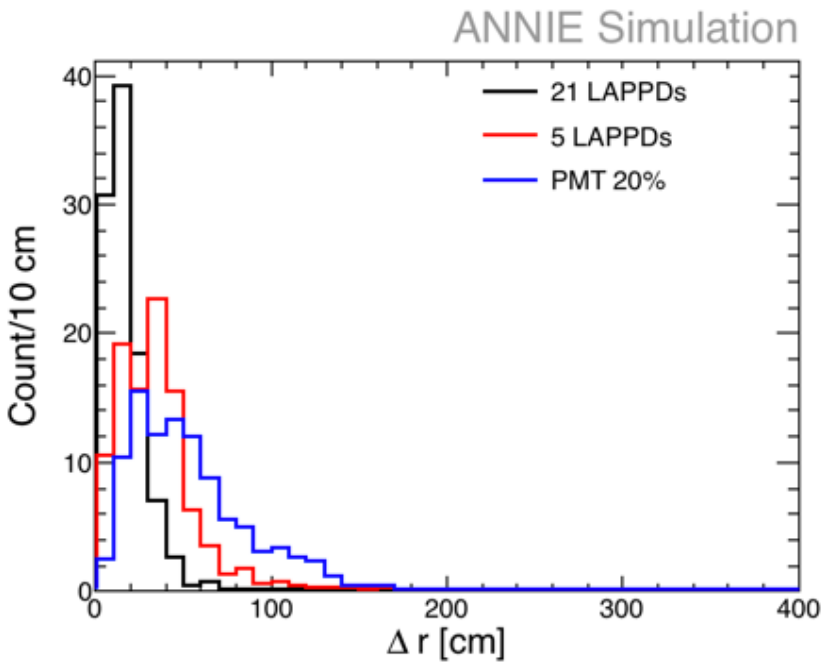
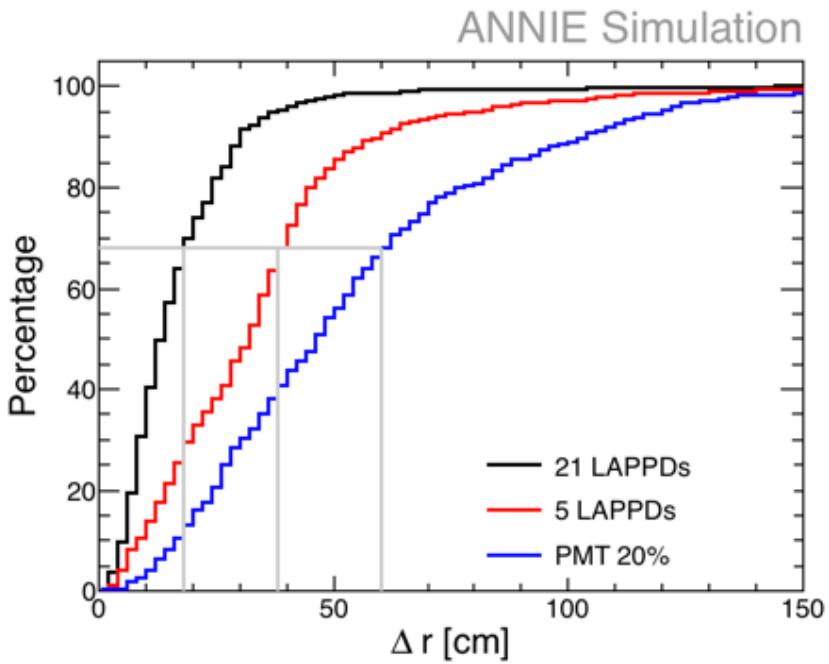




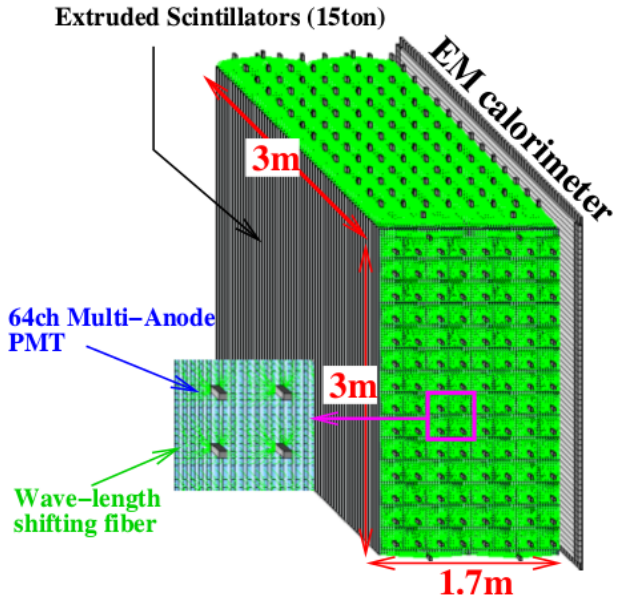
LAPPDs greatly improve the vertex reconstruction

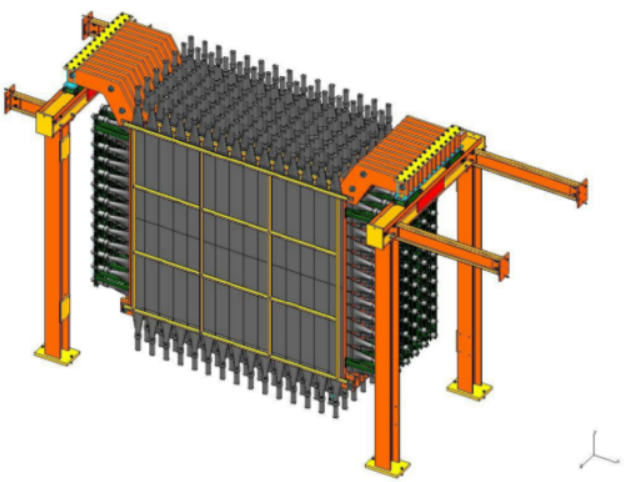
Conclusion and take-home message

- The goals of ANNIE:
  - **Study the multiplicity of final state neutrons from neutrino-nucleus interactions in water**
  - **First test of LAAPDs in a neutrino detector**
- Phase I is a success and demonstrates Phase II is feasible with a low neutron background
- ANNIE is moving into Phase II:
  - LAPPD prototypes being tested and meeting specifications
  - Other tank and MRD instrumentation available
  - Neutron background low enough for physics measurement
- **ANNIE will take physics data in 2018**
- We are discussing adding wbLS for a possible Phase III

Back-up

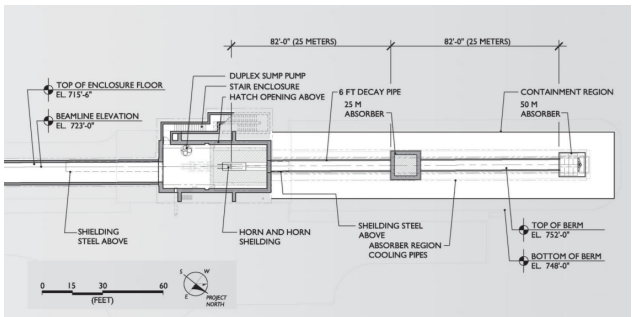
SciBooNE

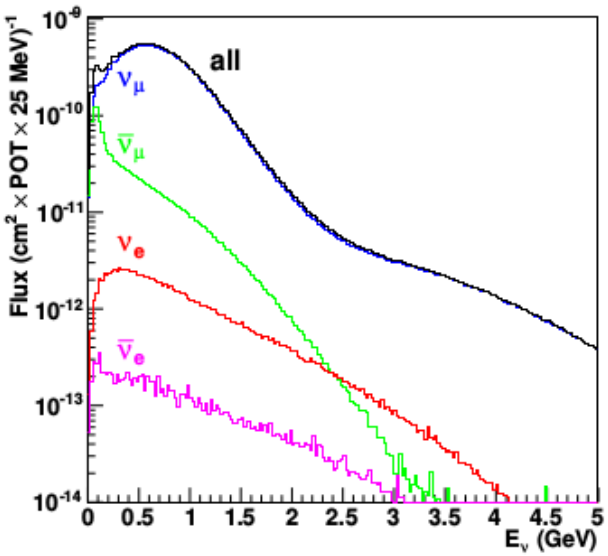




- SciBar: Scintillator tracking detector (14'000 bars, 14 tons)
- Electron Catcher: 2 planes of calorimeter (lead and scintillating fibers)
- Muon Range Detector
- Measurement of CC-QE, CC-$\pi^{\pm}$, CC-π^{0}, NC-ES cross-sections

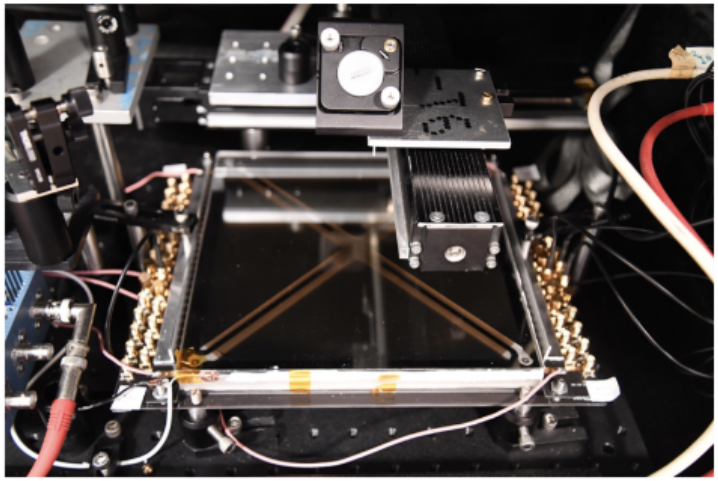
Booster Neutrino Beam

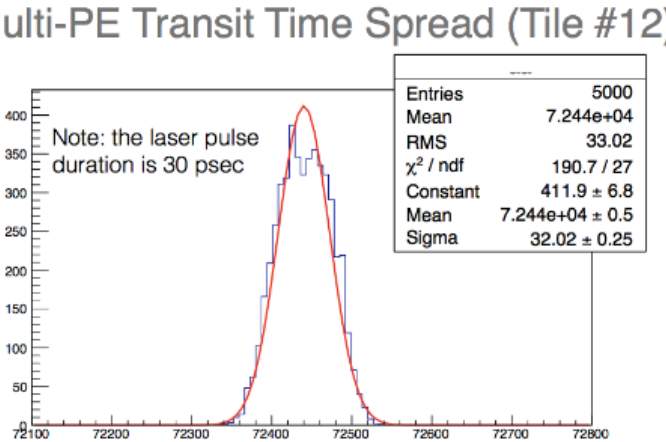


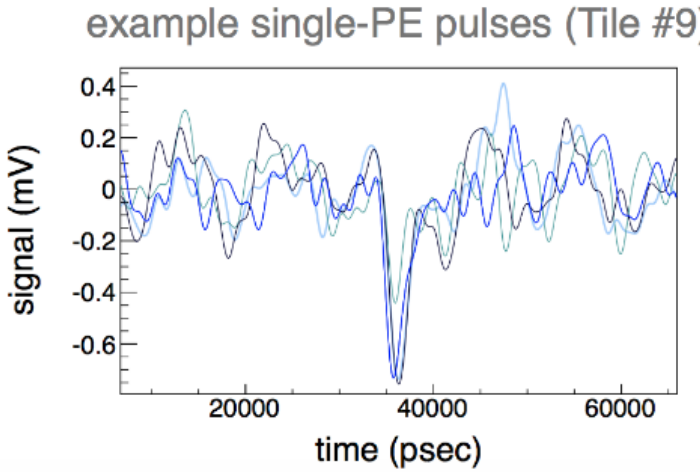


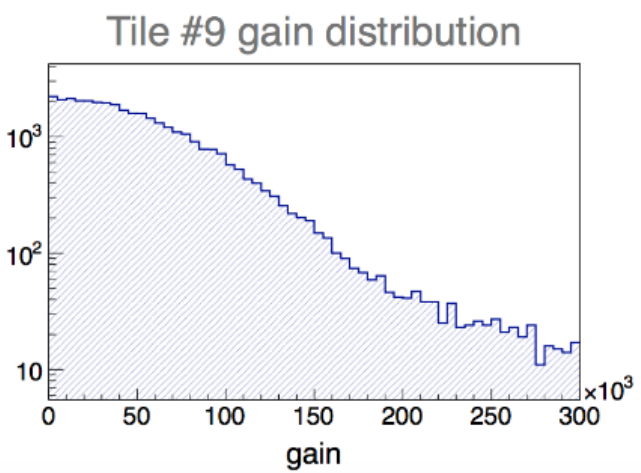
- 8 GeV protons from Booster beam
- Beryllium target, reversible horn polarity
- Mean neutrino energy of 700 MeV
- Composition: 93 % of ν_μ, 6.4 % of $\bar{\nu}_\mu$ and 0.6 % of $\bar{\nu}_e$ and ν_e

LAPPD testing at ISU







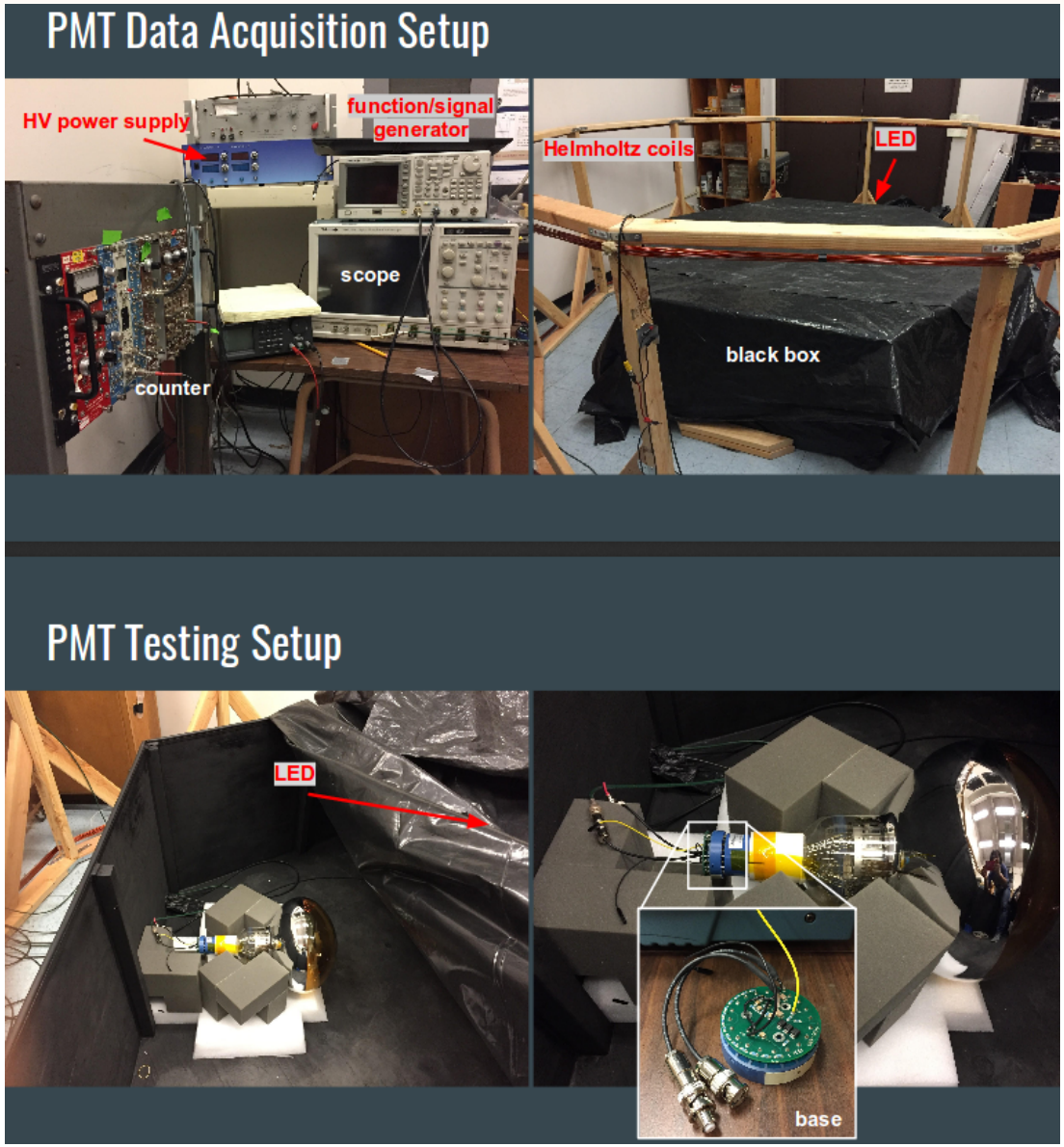


M. Wetstein, ISU

Jingbo Wang, TIPP, 2017 -5-25, Beijing

Slide 20

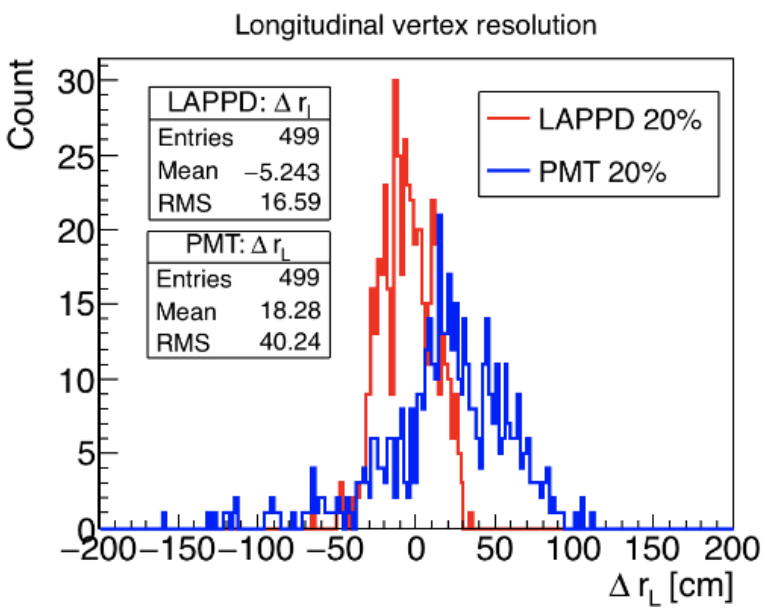
PMT testing at UC Davis

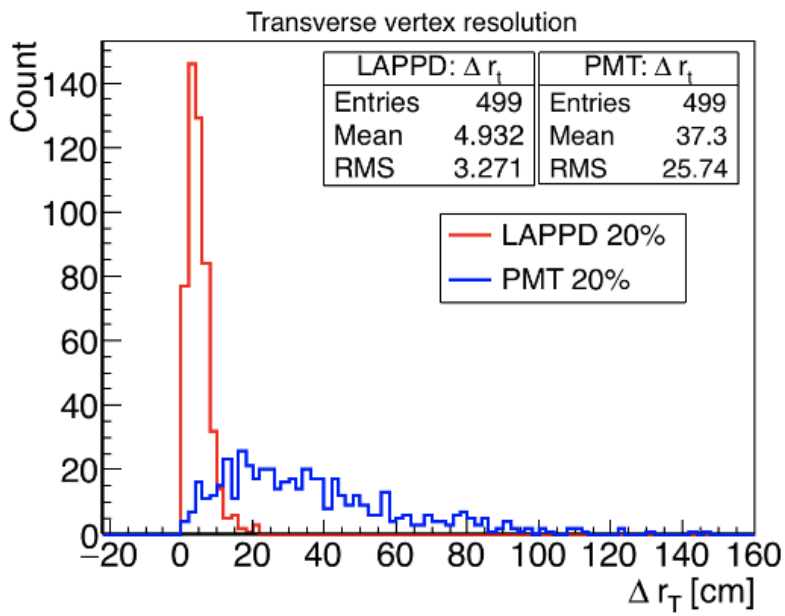


Credit: Julie He, UC Davis

Vertex reconstruction in Phase II

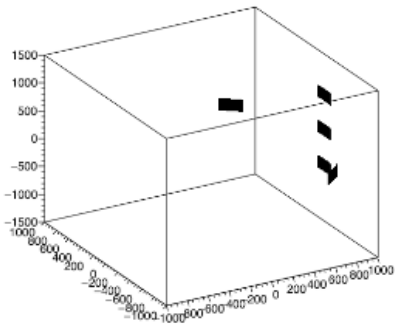
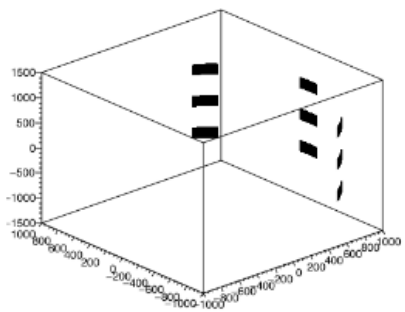
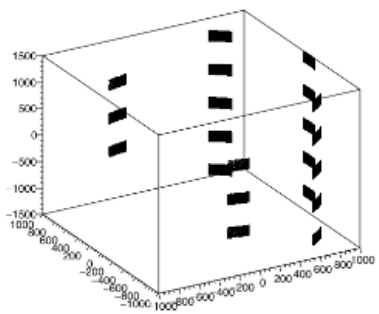
- **Comparison between LAPPDs and PMTs**
  - Sandbox simulation files: 20% LAPPD coverage VS 20% PMT coverage
  - 500 events
  - 122 LAPPDs or PMTs
  - Simulate a range of neutrino energies
  - Reconstruct full muon tracks

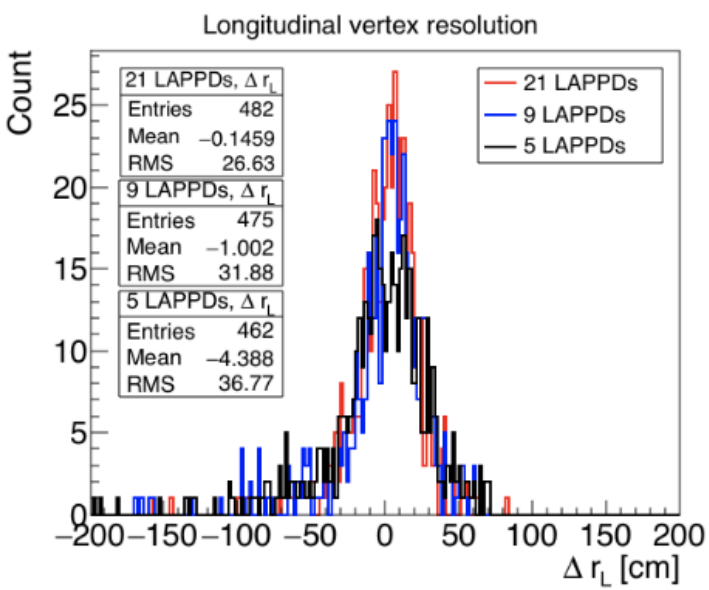


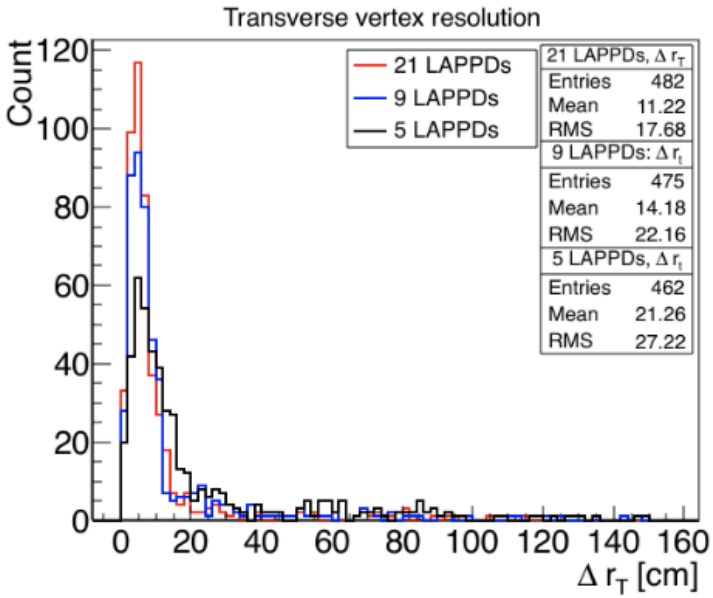


Vertex reconstruction in Phase II

- **Study on the number of LAPPDs**

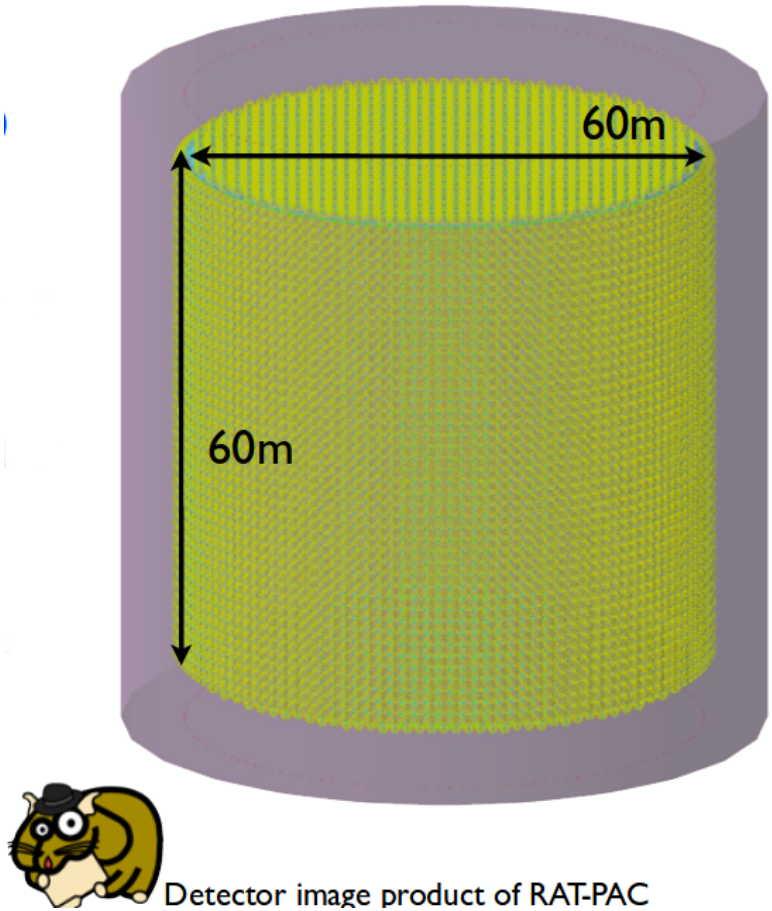








A possible Phase III? - ANNIE as Theia test stand

- The Theia project
  - 50 kt detector, water-based liquid scintillator (wbLS) as a medium
  - Broad range of neutrino physics (LBL, $0\nu2\beta$, geo-ν, etc..)
  - Proto-collaboration has been formed
- ANNIE seems like a good candidate to be a Theia test stand
- A Phase III with wbLS in the tank could be foreseen
- Lot of interest from the Theia proto-collaboration
- FNAL showed interest in Theia as well



Detector image product of RAT-PAC

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International Aspects

The THEIA project investigates the feasibility of a future large-volume water-based liquid scintillator detector for low-energy neutrino astrophysics and oscillation physics. The deployment of the THEIA detector at the deep levels of the Homestake Mine (South Dakota) would be an attractive possibility, both because the considerable rock overburden allows for a rich astrophysical neutrino program and the alignment of the site with the future GeV neutrino beam from the Long Baseline Neutrino Facility (LBNF) at Fermi National Lab.

Several neutrino working groups (listed below) based at German universities and research institutes have declared their interest in further exploring this opportunity. To this end, they have joined the emerging international THEIA proto-collaboration and plan to contribute to R&D efforts on target scintillator, optical detection, DAQ electronics and neutrino event reconstruction as well as detailed studies of the potential physics reach. Fermilab welcomes the efforts that will be undertaken by the groups along these lines as an active contribution towards exploitation of the full potential of the LBNF program.

Jan/2017, Endorsement from Fermilab to German groups to play a leading role to exploit the LBNF program.

Some more calibration

Tank calibration

- Set of scintillator paddles installed on top of the tank
- Coincidence between 2 paddles $\rightarrow$ Muon in the tank or the NCV
- Used to monitor water quality and NCV response
- 4 LEDs installed on top of the tank
- Monitor water transparency and PMT response